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Calibration Service for Low-Loss, Three-Terminal Capacitance Standards at 100 kHz and 1 MHz

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CONTENTS

	Page
FIGURES	v
TABLE	vi
ABSTRACT	1
1.0 Introduction	1
2.0 Description of Service	2
3.0 Description of Measurement Systems	3
3.1 Primary Capacitance Standards	4
3.2 Low-Frequency (1 kHz) Determination of Capacitance	5
3.3 High-Frequency Determination of Residual Impedance	5
3.4 Multifrequency LCR Meter	5
4.0 Theory of the Measurement System and Analysis of Uncertainties	6
4.1 Measurement at 1 kHz	6
4.2 Capacitor Model for Higher Frequency	9
5.0 Quality Assurance Programs	14
6.0 References	16
Appendix A. Detailed Discussion of Measurement Methodology	17
Appendix B. Typical Report of Calibration	22

FIGURES

		Page
Figure 1	Procedure for determining high-frequency values of customer's three-terminal capacitance standards.	4
Figure 2	Transformer ratio bridge circuit.	7
Figure 3	Circuit model of capacitor with residual impedances.	9
Figure 4	Schematic diagram of circuit used to determine the residual inductance of a capacitor.	10
Figure 5	Frequency vs. percent correction for C for a 1000 pF capacitor having a residual impedance of 50.0 nH	11

TABLES

		Page
Table 1	Total uncertainties in percent for three-terminal capacitor calibration [nominal value of capacitor (pF)].	2
Table 2	Summary of uncertainties in the transformer ratio bridge at 1 kHz.	8
Table 3	Uncertainty in the determination of C due to uncertainty in the value of lead inductance.	11
Table 4	Summary of uncertainties from the three experiments.	13
Table 5	Total uncertainty in measuring three-terminal capacitors. . .	13

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This document describes the three-terminal, capacitance calibration service at 100 kHz and 1 MHz at the National Institute of Standards and Technology, Boulder Laboratories. The document discusses the purpose of the service, contact points for initiating the service, what capacitors are appropriate for calibration, the measurement methods used, the instrumentation used for the measurements, and an analysis of the errors in the measurement. It also lists the calibration uncertainties for the stated frequencies and capacitances. Finally, the document discusses the quality assurance programs used at NIST to insure the integrity of the calibrations.

Key words: calibration; capacitance; lead inductance; measurement; three-terminal; uncertainty.

1.0 Introduction

Capacitors are used in electronic, electrical, and electromechanical systems. As one of the basic building blocks in electrical circuit theory and application, they are pervasive in all the above applications. Specifications for testing during manufacture and use are contained in military specifications, American Society for Testing and Materials (ASTM) documents, and many other documents.

A growing military-government-industrial need is for capacitance standards that support digital instrumentation systems that are now available. This new generation of equipment measures capacitance over a broad frequency range, to a relatively high accuracy, at high speed and in both the three- and four-terminal modes.

The Department of Defense (DOD), the National Aeronautics and Space Administration (NASA), other government agencies, and manufacturers of electrical components and instrumentation require traceability to the National

Institute of Standards and Technology (NIST) in order to ensure the quality of their product or service.

The National Institute of Standards and Technology, Division 813.01 (Microwave Metrology), is responsible for the calibration of impedance standards in the frequency range 100 kHz to 300 MHz. Calibration services for capacitors at frequencies lower than 10 kHz are available from the NIST laboratories in Gaithersburg, Maryland [1]. This paper discusses the measurement procedure and the instrumentation used in the measurement of three-terminal capacitors (0.01 to 1000 pF) at the frequencies 100 kHz and 1 MHz. It also discusses the maintenance of the unit of capacitance and the analysis of errors in the NIST three-terminal capacitance calibration service.

2.0 Description of Service

Test frequencies of 100 kHz and 1 MHz are used for capacitors having nominal values of 0.01, 0.1, 1, 10, 10^2, and 10^3 pF. The capacitance value of the standard is reported while the value of conductance, or dissipation factor, is not included. The total uncertainties of the calibrations are shown in Table 1.

Table 1. Total uncertainties in percent for three-terminal capacitor calibration [nominal value of capacitor (pF)].

	Nominal value of capacitor					
Frequency	0.01 pF (%)	0.1 pF (%)	1.0 pF (%)	10 pF (%)	100 pF (%)	1000 pF (%)
100 kHz	1.96	0.38	0.10	0.05	0.03	0.05
1 MHz	1.96	0.38	0.10	0.05	0.03	0.09

Capacitance standards that are to be calibrated in the radio frequency (rf) range should have residual series inductance less than 100 nH and temperature coefficients that are on the order of 20 to 40 ppm/°C between 20 and 70°C.

Of the two types of standards most commonly calibrated, one is equipped with BNC jack-type connectors at a spacing of 3.8 cm on centers, and the other is equipped with GR Type 874 connectors at a spacing of 2.85 cm on centers. Both standards are constructed as shielded, parallel-plate capacitors with air as the dielectric.

Capacitance standards submitted to NIST for calibration should be in good working order; that is, the terminals should be thoroughly cleaned and there should be no loose components. The capacitors should be carefully packed for protection from physical damage. It is also recommended that the customer compare the standard with other capacitance standards just before shipment to NIST and again immediately upon its return. Since the capacitors are of parallel plate construction, they are susceptible to both mechanical and thermal stress (a common occurrence during shipment). When the capacitors are stressed, the capacitance value can change appreciably. The customer's measurements ensure that changes have not occurred in transit.

In some circumstances where the customer has good capacitance measurement capabilities at 1 kHz (uncertainties less than 50 ppm), it may not be necessary to submit capacitors smaller than 10 pF to NIST for calibration at 100 kHz and 1 MHz. This is because high-quality, three-terminal, air dielectric capacitance standards constructed for rf use have low residual series inductance ($<0.1\ \mu H$). With this low lead impedance, it may be assumed that to an uncertainty of 0.01 percent the residual series inductance will not change the "effective capacitance" of standards of 10 pF or less at 100 kHz and 1 MHz.

3.0 Description of Measurement Systems

The measurement systems and standards necessary to assign a value to a customer's standard at the calibration frequencies are shown in Figure 1.

The final value assigned to a customer's standard is a function of several components, capacitance standards in which the unit of capacitance is maintained, and transfer devices (that is, bridges or other independent experiments that make possible the transfer of the unit from known standards to the customer's standards). More specifically, the components of the system are shown in Figure 1.

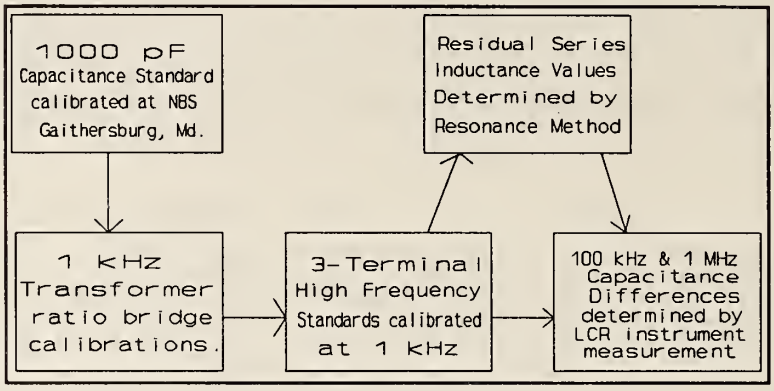

Figure 1. Procedure for determining high-frequency values of customer's three-terminal capacitance standards.

3.1 Primary Capacitance Standards

The unit of capacitance is maintained in six banks of standards. Each of these six banks includes three capacitors with one bank for each nominal value, that is, 0.01, 0.1, 1, 10, 10^2, 10^3 pF. These standards are regularly intercompared to determine the change of capacitance of individual capacitors with respect to the group mean; and, yearly, the bank of standards is calibrated in terms of one capacitor that is sent to NIST-Gaithersburg for calibration. Thus the drift rate, the standard deviation of the measurement, and other important parameters can be determined for the capacitance standards.

3.2 Low-Frequency (1 kHz) Determination of Capacitance

A transformer ratio bridge allows the direct calibration of an unknown capacitor in terms of a known standard to a very high degree of accuracy. Measurements are made only at 1 kHz. These measurements provide useful information about the standards and the measurement system. The accuracy of this bridge degrades rapidly above 1 kHz, so measurements are considered valid only at this frequency.

3.3 High-Frequency Determination of Residual Impedance

The determination of the high-frequency residual impedance of capacitance standards is discussed in several papers [2,3]. In the experiment discussed in these papers, the residual inductance of the secondary standards was determined using resonant techniques. The effective capacitance at 100 kHz and 1 MHz can be calculated using the parameters determined in this experiment in a typical model of a capacitor with series inductance and resistance.

3.4 Multifrequency LCR Meter

This instrument is used to compare known standards of capacitance with the standards to be calibrated at the frequencies of 100 kHz and 1 MHz. The instrument compares the in-phase and quadrature voltages across the unknown capacitor with those across a standard resistor which carries the same current. The LCR meter displays the capacitance based on these parameters [4].

4.0 Theory of the Measurement System and Analysis of Uncertainties

The relationship used to determine the value of a customer's standard is

$$C_{unk} = [(C_{s1}+C_{s2}+C_{s3})/3] + \frac{1}{3} \times \sum_{j=1}^{3} [C_{uj} - (C_{1_j}+C_{2_j}+C_{3_j})/3] . \quad (1)$$

In Eq.(1), C_{unk} is the effective value of the capacitor being calibrated; the $C_{si}(i=1,2,3)$ are the values of the NIST standards as determined by two experiments, that is,

$$C_{si} = C^{*}{}_{si} + dC_{si} , \quad (2)$$

where

C^{*}_{si} is the value determined at 1 kHz by intercomparison with the NIST primary standards,

dC_{si} is the high-frequency correction for the standard (for either 100 kHz or 1 MHz) as described in [2,3].

The C_{ij} in Eq.(1) are the values of the NIST standards measured at either 100 kHz or 1 MHz using the digital impedance meter. C_{uj} is the value of the unknown being calibrated as it is measured by the meter.

The sources of systematic and random error in the measurement can be identified from the three experiments (measurement of the standards at 1 kHz, measurement of the standards and the unknown at the calibration frequency, and the determination of the lead impedance) used to determine the final values of the standards. There are both systematic and random errors in each of the experiments. Thus, we will consider the three experiments separately for analysis of error and will then combine the errors at the end of the discussion.

4.1 Measurement at 1 kHz

The measurement of capacitance at audio frequencies using a transformer ratio bridge has been discussed in a number of papers [5]. A circuit diagram of the bridge, without the shielding, is shown in Figure 2.

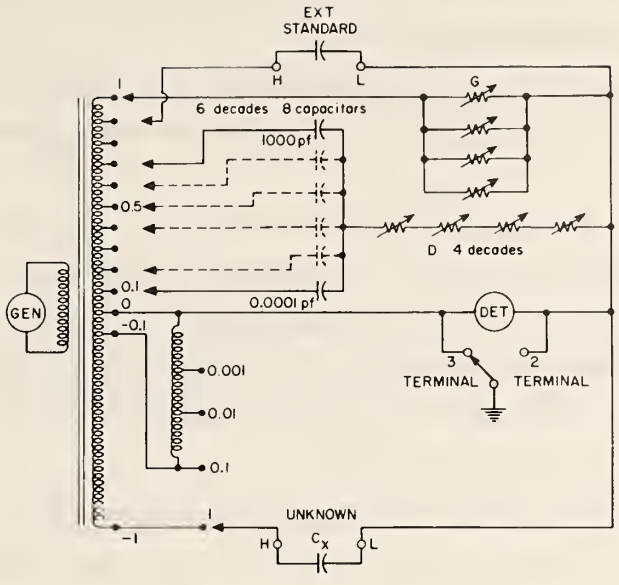

Figure 2. Transformer ratio bridge circuit.

The equations of balance for an individual measurement are

$$C_{unk} = M_c \times C_{std} + \sum_i R_i \times C_i \quad , \tag{3}$$

and

$$G_{unk} = M_g \times G_{std} + \sum_j R_j \times G_j . \tag{4}$$

In Eqs. (3) and (4), M_c is the ratio of intercomparison; usually either 1 or 0.1. C_{std} is the primary standard; R_i and R_j are the ratio settings for the various dials ($-0.1 \leq R_i \leq 1.0$); and C_i and G_j are the fixed capacitors and resistors for the various dial settings. The following are errors that occur in the measurement.

δ_1 is the uncertainty in the ratio of the bridge arm (M). This uncertainty is discussed in [6,7]. For a ratio of 1 it is easily determined, but for a ratio of 0.1 the calibration scheme is difficult and the uncertainty will be estimated.

δ_2 is the uncertainty in the value of the individual dials and is cumulative. At present, the bridge dials are adjusted using a scheme discussed by the manufacturer [8].

δ_3 is the total uncertainty in the primary standards value. This value is determined by the total uncertainty assigned to the capacitor by NIST, Gaithersburg.

δ_4 is the standard deviation of the measurement process and is determined using measurement designs and least-squares fit of the data.

δ_5 is an uncertainty estimate of the primary standards due to temperature variation in the laboratory, handling of the capacitance standards, and so on. The number is based on manufacturer's specifications and past experience with these standards.

δ_6 is the uncertainty due to lead impedance, that is, the length of coaxial lead needed to connect the capacitors to the measurement system. For measurements at 1 kHz using 1000 pF capacitors, this uncertainty would be less than 1 ppm. It is smaller for the other standards. Since it is less than 1 ppm in all cases it is not included in Table 2.

The uncertainties present in assigning values to the six banks of standards at 1 kHz and the total uncertainty (U) of these measurements are summarized in Table 2.

Table 2. Summary of uncertainties in the transformer ratio bridge at 1 kHz.

Nominal Value	δ_1 (%)	δ_2 (%)	δ_3 (%) (pF)	δ_4 (%)	δ_5 (%)	U (%)
1000[1]	0.0	0.0	0.001	0.0000	0.0002	0.0017
1000	0.0	0.0	0.0017	0.0000	0.004	0.0076
100	0.001	0.0	0.0017	0.0002	0.004	0.0078
10	0.001	0.005	0.0078	0.0002	0.004	0.015
1	0.001	0.005	0.015	0.0023	0.008	0.032
0.1	0.001	0.05	0.032	0.023	0.008	0.124
0.01	0.001	0.5	0.124	0.23	0.008	1.12

[1]The first row of data displays the uncertainties that are assigned to the NIST low-frequency, primary standards, i.e., those that are calibrated at NIST, Gaithersburg.

In Table 2 the δ's are one standard deviation (either estimated or documented values). U is the overall uncertainty assigned to a standard. The uncertainties listed in Table 2 were combined according to the relationship suggested in [9]. Thus, the overall uncertainty in the 1 kHz capacitance measurement is determined using the relationship

$$U = 3 \times \left(\delta_4^2 + \sum_i \frac{\delta_i^2}{3}\right)^{\frac{1}{2}}. \tag{5}$$

In this equation, δ_4 is the standard deviation obtained from repeated measurements, and the δ_i are estimates of the systematic uncertainty and do not include δ_4.

4.2 Capacitor model for higher frequencies

The effective capacitance of a standard capacitor is a function of a number of variables at any measurement frequency. The primary causes of this variation are residual inductance and resistance inherent in the construction of a three-terminal capacitor. At 1 kHz these residuals are not apparent, but at higher frequencies such as 100 kHz and 1 MHz they can cause a measurable change in the effective capacitance value. A model of a capacitor with its residuals is shown in Figure 3.

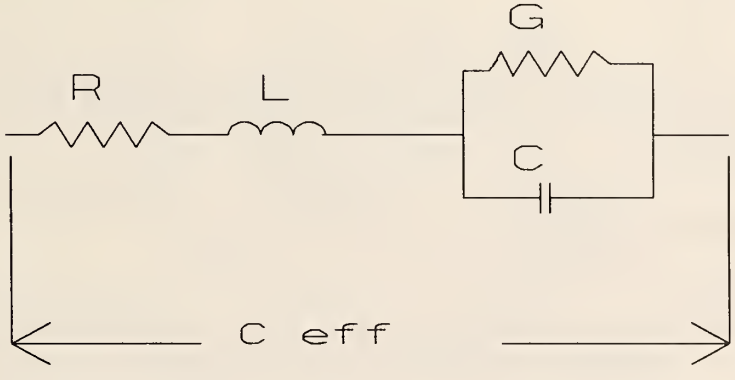

Figure 3. Circuit model of capacitor with residual impedances.

The components are L, an inductance that exists primarily in the leads; R, a resistance that again exists primarily in the leads and G, a parallel

conductance which is primarily a dielectric loss occurring in the isolating supports for the plates of the capacitor. For high-frequency, low-loss capacitors the major source of change below 10 MHz is the inductance of the wire from the connector to the capacitor plates. The equation for the effective capacitance of the model reduces to

$$C_{eff} = \frac{C}{(1-\omega^2 \times L \times C)} \tag{6}$$

where ω is the radian frequency. This assumes that the frequencies are below 10 MHz, and that $R < 0.1\ \Omega$, $L < 100\ \mu H$, and $G < 10^{-7} S$. Since the residual components do not change significantly with frequency, the effective value of capacitance at high frequency can be based on a precise measurement of the value at low frequency.

An experiment done at NIST is described in [3]. By determining the frequency at which resonance occurs and knowing precisely the 1 kHz values of the various capacitance terms in the circuit, we can determine the series inductance in the circuit. The measurement circuit is shown in Figure 4.

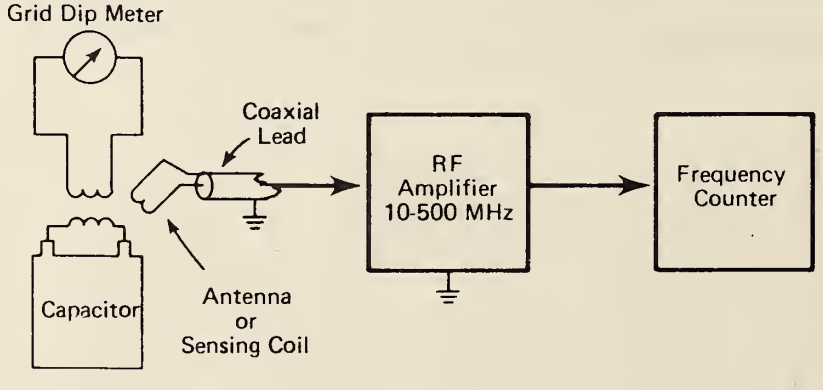

Figure 4. Schematic diagram of circuit used to determine the residual inductance of a capacitor.

This experiment was carried out on all the NIST high-frequency, three-terminal standards. A typical result of the experiment is shown in Figure 5. Below 700 kHz the change in capacitance is less than 0.1 percent of the value. At approximately 7 MHz the change in capacitance value is approximately 10 percent.

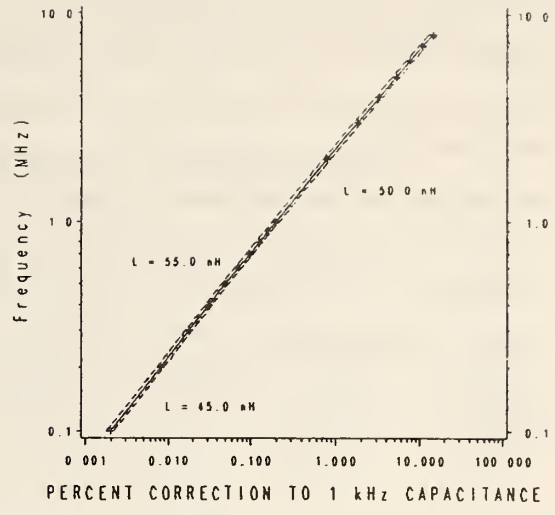

Figure 5. Frequency vs. Percent Correction for C for a 1000 pF capacitor having a residual inductance of 50.0 nH.

The major sources of error in the resonance experiment are the inaccuracy in the determination of the resonant frequency, mutual coupling between the shorting link and the detector coil, and error in the calculation of the inductance of the shorting element. The overall uncertainty of the experiment is calculated to be less than 10 percent. Thus, the error in the capacitance value can abe determined from the equation,

$$\delta C = \frac{2 \times \omega^2 \times C^2 \times \delta L}{(1 - \omega^2 \times L \times C)^2} \quad . \tag{7}$$

Table 3 contains the uncertainties with respect to frequency and capacitance magnitude.

Table 3. Uncertainty in the determination of C due to uncertainty in the value of lead inductance.

Frequency Align	Nominal Value of Capacitance Standard: 1000 pF	100 pF	10 pF	1 pF
	Uncertainty of Value in Percent			
100 kHz	2.5×10^{-4}	2.5×10^{-5}	2.5×10^{-6}	2.5×10^{-7}
1 MHz	2.5×10^{-2}	2.5×10^{-3}	2.5×10^{-4}	2.5×10^{-5}

Measurement at 100 kHz and 1 MHz

The multi-frequency LCR system is based on a different measurement principle than the traditional immittance bridge. The traditional approach to the measurement of an unknown impedance has been to utilize passive standards such as resistors and capacitors in a network so that the unknown impedance can be determined uniquely in terms of the other passive standards in the

network. The traditional circuit is arranged so errors due to stray capacitance, for example, are minimized through passive ground circuits. In the present system there are two elements in the circuit, the unknown and a reference resistor which are connected in series. When the unknown is connected to the system, internal circuitry adjusts the magnitude and phase of the current through the unknown so that the detector junction between the two standards is at ground potential. The complex voltages are then measured across the unknown and the reference resistor. Knowing the magnitude of the standard and the ratio of the voltages, the value of the unknown can thus be determined from Eq. (8),

$$Z = \frac{R_s \times V_z}{V_s} \quad , \tag{8}$$

where the voltages V_z and V_s are complex.

Due to the complexity of the circuitry involved, estimates of the systematic uncertainties are extremely difficult. Thus, to determine the uncertainties of the system, a more pragmatic approach was used. Since the system is used in measuring differences between an unknown and a known capacitor of nearly the same magnitude, experiments were done in which three capacitors of known value at the test frequencies were measured a large number of times. In each set of measurements one of the standard capacitors was also considered to be the unknown and measured as such. Thus, from Eq. (1)

$$\delta_j = C_{uj} - (C_{1j} + C_{2j} + C_{3j})/3 \quad , \tag{9}$$

the δ_j are determined from the measurements. The same δ_j can be calculated since the capacitance of each capacitor is known. In the actual experiments a fourth capacitor whose lead impedance was known was also used and treated as the unknown. The difference between the calculated δ_j and the measured δ_j was then determined. Both the systematic uncertainty and the random uncertainty can be determined for the various capacitances and for the various frequencies. Table 4 summarizes the uncertainties determined for this

experiment as well as listing the uncertainties determined for the other experiments in the chain.

Table 4. Summary of uncertainties from the three experiments.

Nominal value (pF)	1 kHz Uncertainty (%)	A 100 kHz (%)	A 1 MHz (%)	B 100 kHz (%)	B 1 MHz (%)	σ 100 kHz (%)	σ 1 MHz (%)
1000	0.0076	0.00025	0.025	0.013	0.013	0.0023	0.0025
100	0.0078	0.00003	0.0023	0.0021	0.0021	0.0011	0.0014
10	0.0153	-	0.0003	0.0055	0.0050	0.0016	0.0016
1	0.032	-	-	0.003	0.004	0.0024	0.0024
0.1	0.124	-	-	0.01	0.002	0.021	0.016
0.01	1.12	-	-	0.02	0.037	0.1	0.1

In Table 4, the A's are the systematic uncertainties from the experiment determining residual inductance. The columns labelled B are the systematic uncertainties in the LCR system at the various magnitudes and frequencies determined by measuring differences, and the σ's are the standard deviations of the difference measurements. The second column is the uncertainty determined from the 1 kHz calibration of the standards.

Combining uncertainties in the same manner as was done for the 1 kHz experiment, we arrive at the total uncertainties for the various frequencies and magnitudes of capacitance as shown in Table 5.

Table 5. Total uncertainty in measuring three-terminal capacitors.

Nominal Capacitance Value (pF)	Total Uncertainty at 100 kHz (%)	Total Uncertainty at 1 MHz (%)
1000	0.046	0.088
100	0.024	0.026
10	0.049	0.049
1	0.096	0.096
0.1	0.378	0.375
0.01	1.960	1.960

5.0 Quality Assurance Programs

A number of programs assure the quality of the three-terminal capacitance calibration service.

Primary Standards. These standards are intercompared periodically at 1 kHz. The measurement scheme is a balanced design. Values for the standards are determined using least-squares techniques. The design includes an offset in the measurement equations, to account for any fixed bias that may occur in the circuit. The results of the measurements and calculations are kept on control charts. Control charts of the following quantities are monitored.

1. $C_i - C$, the difference between the measured values for the individual capacitors and the group mean.
2. σ^2, the variance of the least-squares fit of the measurement data.
3. Offset, the fixed bias in the measurement.

Secondary Standards. There are three secondary standards for each nominal value that is calibrated between 0.01 and 1000 pF. These standards are intercompared at 1 kHz using balanced designs. They are intercompared at 1 kHz with the primary standards once a year using step-up techniques. Control charts are kept for these standards as for the primary standards.

Use of the control charts assures that the status of the individual capacitors is well characterized and that the performance of the measuring instrumentation is carefully monitored.

The performance of the bridge is also monitored by noting the value of conductance that is measured during any measuring scheme. Since all capacitors measured have extremely small conductance, a bridge balance measuring a conductance above 100 pS would be an indication that the switching apparatus on the bridge dials needs cleaning.

Other quality assurance procedures are used in the handling and storing of the capacitance standards. All standards are measured and stored in an upright position so that the parallel plates will receive a minimum amount of mechanical stress. Care is taken in the handling of the capacitors to avoid all mechanical shocks to the standards. The standards are also kept and measured in a temperature-controlled room. The total thermal change experienced by the capacitors during the tests is less than 3°C.

Quality assurance procedures followed in the high-frequency measurement of the capacitors are discussed in Appendix A.

This technical note describes the program for the calibration of three-terminal, low-loss capacitors at high frequencies. The types of capacitors that may be calibrated and the various experiments and instrumentation that are used in the experiments to arrive at a final calibration value are discussed. Finally, the theory of the measurement and an analysis of the errors in the calibration procedure are presented.

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APPENDIX A
Detailed Discussion of Measurement Methodology

After an initial warm-up interval and calibration of the digital capacitance (LCR) meter, NIST standard capacitors and the capacitor to be calibrated are connected to the capacitance meter in a prescribed order and measured. Figures A-1 and A-2 are sample data sheets of an actual set of calibration runs.

To describe the measurement and data analysis procedure, we will use the sample data sheets and discuss the specific features identified by the large print capital letters.

A. These are the LCR meter readings for each of the three NIST standards and the unknown as they are connected to the meter in a particular order as specified by the computer program.

B. These corresponding conductance values determined by the LCR meter are irrelevant because they are not utilized in the calibration procedure. However, if a large conductance value is observed, it would indicate a faulty standard or unknown.

C. Capacitance of standard C_s is the average of the calculated values for the three NIST working standards which are derived by extrapolation in the computer program from the 1 kHz capacitance values and the residual series inductances [3]. Each of the three NIST working standards has a value at the calibration frequency given by

$$C_{en} = \frac{C_{on}}{1-\omega^2 L_{r(n)} C_{on}}, \quad n = 1,2,3 \quad , \tag{10}$$

where C_e is the effective capacitance at the calibration frequency; C_o is the low-frequency (1 kHz) value of capacitance; L_r is the residual

series inductance; ω is the angular frequency in radians per second; and

$$C_s = \frac{C_{e1} + C_{e2} + C_{e3}}{3}. \tag{11}$$

D. Three measurements (N = 3) are made for each unknown, usually over a period of about three days. This is the number of the current run being performed in the series of three. The measurements for all four capacitance standards over the three runs are stored in an array.

E. These are the data stored from the previous six measurement procedures made at this frequency involving a particular set of three NIST working standards. Each row of data corresponds to a specific NIST working standard. Rows are in the same sequence as that in which the measurements are to be performed. Each column pertains to a particular calibration run, with the most recent appearing at the right side of the page. With successive runs, each column will move one position to the left, with the leftmost column being eliminated from the stored data. This may be observed from the sequence of three runs performed on the capacitor (serial number 256). Note, however, that three runs for a particular unknown need not necessarily correspond to three consecutive runs. Runs for other unknowns may intercede if there is more than one unknown of a specific type in the laboratory for calibration at a particular frequency at any time.

These data are the net differences between the measured capacitance value for each NIST working standard and the group average of these values for a single calibration run,

$$d_i = C_i - \frac{C_1 + C_2 + C_3}{3}, \quad i = 1,2,3. \tag{12}$$

These are values in picofarads represented to five decimal places.

F. These are the standard deviations stored on disk which were calculated during the previous calibration run. These are the cumulative standard deviations for all previous runs for each of the three NIST working standards, in sequence, at this calibration frequency with this connector configuration.

G. These are the cumulative averages of difference from the measured mean for the number of runs shown in (H).

H. This is the total number of previous runs used in computing cumulative averages in G.

I. These are the net differences for each of the three NIST standards for the current calibration run. For each run j these values are obtained for the three NIST standards and for the unknown:

$$d_i = C_i - C_{sj}, \quad i = 1,2,3,4, \tag{13}$$

where

$$C_{sj} = \frac{C_{1j} + C_{2j} + C_{3j}}{3}. \tag{14}$$

J. These are the values for the cumulative averages of the data for each of the NIST working standards, at this frequency, updated to include the current run. For each NIST working standard, at both 100 kHz and 1 MHz, both with and without the GR874-QBJA adapters used in the calibration of capacitance standards. The cumulative average is plotted on a control chart, as well as the net difference from the group average for each run, in order to track the history of the behavior, over time, of that standard. Note that for each NIST working standard, there are four control charts.

K. These are the new values calculated for the cumulative standard deviations which include all previous runs and the current calibration run. The standard deviation is calculated for each run using the Method of Provisional Means [10].

L. This is the updated total number of calibration runs performed for this nominal capacitance value at this calibration frequency using this connector configuration.

M. This is the bias for the unknown. It is the net difference between the measured capacitance value for the capacitance standard to be calibrated and the group average, for a single run, of the three NIST working standards,

$$b_j = C_{4j} - C_{sj} = d_{4j}. \tag{15}$$

This is the value in picofarads represented to five decimal places. Current values and values for any previous runs for this unknown are printed out.

N. These are the values, in picofarads, of the capacitance measurements for the three NIST standards and an unknown for the current run and for any previous runs for this unknown. These quantities are printed out only for runs 2 and 3.

O. These are the values, in microsiemens, of the conductance measurements for the three NIST standards and an unknown for the current run and for any previous runs for this unknown. These quantities are printed out only for runs 2 and 3.

P. This information is printed out only on the final run (run 3).

Q. These are the average data for the three NIST working standards over the sequence of three runs for this unknown.

$$\overline{d_i} = \frac{1}{N}\sum_{j=1}^{N} d_{ij},\ c = 1,2,3,4; N = 3. \tag{16}$$

R. These are the standard deviations for the three NIST working standards over the sequence of three runs for this unknown.

S. This is the average of the value of the bias for the unknown over the three runs.

$$\overline{b} \equiv \overline{d_x} = \frac{1}{N}\sum_{j=1}^{N} b_j, \quad N = 3, (x = 4). \tag{17}$$

APPENDX A-1

THREE TERMINAL CAPACITANCE CALIBRATION

PROGRAM USED IS 3TERMCAP

TEST CONDITIONS

****

NBS TEST NO.:800000 DATE:3 Jul 1991

MANUFACTURER:GR TIME:09:53:10

MODEL/TYPE:1403_A OPERATOR:PJM

SERIAL NO.:123456

LAB.TEMP.:23.5 PRESSURE (mPa) 83.33916 HUMIDITY(%):39.0

LCR Meter Readings:

****

TEST FREQUENCY:1 MHz DATA Stored in Row 52

	Cap (farads)		Cond (siemens)	
NBS STD S/N 1470	1.003225E-09		1.950000E-06	
NBS STD S/N 1490	1.004130E-09	A	2.300000E-06	B
NBS STD S/N 1512	1.002355E-09		2.050000E-06	
CUSTOMER STD	1.002345E-09		2.050000E-06	

Theoretical ave. capacitance at the frequency 1002.531456 pF. C

CURRENT RUN FOR THIS UNKNOWN IS: # 3 D

---------- DATA INPUT FROM FILE FOR NBS STANDARDS:----------

Previous data (Net Differences):

-.02167	-.01667	-.02167	-.02333	-.02000	-.01167
.90833	.88833	.89333	.88167	.90500	.89333 E
-.88667	-.87167	-.87167	-.85833	-.88500	-.88167

Standard Deviations [pF.]: F

S_d[1] = 0.0111042 S_d[2] = 0.0153959 S_d[3] = 0.0172008

Averages [pF.]: G

Avg[1] = -0.0268351 Avg[2] = 0.8853580 Avg[3] = -0.8585229

TOTAL Cumulative Number of Runs = 88 H

APPENDIX A-2

STATISTICAL INFORMATION (this run) #
****

P	Run 1	Run 2	Run 3
DATE:	3 Jul 1991	3 Jul 1991	3 Jul 1991
TIME:	09:44:15	09:50:11	09:53:10
OPERATOR:	PJM	PJM	PJM
LAB. TEMP.:	23.5	23.5	23.5
BAROMETER:	625.2	625.2	625.2
HUMIDITY:	39.0	39.0	39.0

INPUT VALUES FOR C ARRAY (pF.) AND G ARRAY ( ) O N

1003.23500	2.10000	1003.23500	2.00000	1003.22500	1.95000
1004.14000	2.35000	1004.14000	2.25000	1004.13000	2.30000
1002.34500	2.05000	1002.33500	2.05000	1002.35500	2.05000
1002.35500	2.05000	1002.35000	2.10000	1002.34500	2.05000

----------STANDARD DIFFERENCES FOR THIS SET OF RUNS----------

C(1,J)-C_s(J) (Net Differences)
-.00500 -.00167 -.01167
C(2,J)-C_s(J) (Net Differences) I
.90000 .90333 .89333
C(3,J)-C_s(J) (Net Differences)
-.89500 -.90167 -.88167 Averaged net differences: Q
D_av[1] = -0.0061111pF. D_av[2] = 0.8988889pF. D_av[3] = -0.8927778pF.

New cumulative averages [pF.]:
J Avg[1]' = -0.0268351 Avg[2]' = 0.8853580 Avg[3]' = -0.8585229

Standard deviations: (for N runs) (N=3)
R S[1] = 0.0050918pF. S[2] = 0.0050918pF. S[3] = 0.0101835pF.

New cumulative standard deviations [pF.]:
K S_d[1]' = 0.0111042 S_d[2]' = 0.0153959 S_d[3]' = 0.0172008

NEW TOTAL Cumulative Number of Runs = 89 L

---------- CUSTOMER DATA FROM MEASUREMENTS ----------

B(J)==C(4,J)-C_s(J) (Net Differences for unknown) M
-.88500 -.88667 -.89167

S B_av = -0.8877778
VARIANCE = 1.20370370363E-5 STANDARD DEVIATION = .00346944333233
FACTOR = 5.73020142171
CX= 1001.64367863 pF. WITHIN .0198806091155 pF.
REFERRED TO THE AVERAGE VALUE OF THE THREE NBS STANDARDS.
BOUNDS ON CX REPRESENT 99 PERCENT CONFIDENCE LIMITS

Appendix B

Typical Report of Calibration

U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
ELECTRONICS AND ELECTRICAL ENGINEERING LABORATORY
Boulder, Colorado 80303

REPORT OF CALIBRATION

THREE TERMINAL CAPACITOR
General Radio Company
Type 1403-A, Serial No. 180

Submitted by:

The value given for this capacitor was obtained by comparing it with air-dielectric capacitors of approximately the same value which are maintained as reference standards at the National Institute of Standards and Technology. The values of the NBS reference standards have been determined by an extrapolation procedure as described in NIST Technical Note 1024 "Evaluation of Three-Terminal and Four-Terminal Pair Capacitors at High Frequencies" by R. N. Jones, issued September 1980, available from the address shown in the letterhead above.

The comparisons were made in an ambient laboratory environment of 23 ± 2°C, 40 ± 5 percent relative humidity, and an atmospheric pressure of approximately 8.40×10^4 Pa (630 mm Hg). The uncertainty expression following each measured value is given as the sum of two quantities. The first of these quantities gives the systematic uncertainty. It includes the uncertainty in the value of the reference standards at the calibration frequency and the bias of the instrument used in the comparison procedure. The second of the two quantities in the uncertainty statement gives the random uncertainty derived by taking three times the standard deviation of the mean of the measurement process. Measurements of this item were made three times over a period of several days. Should a single quantity be required to represent the uncertainty, a figure derived by taking the square root of the sum of the squares of the systematic and random uncertainty components may be used.

Test No.
Date of Test:

Three-Terminal Capacitor

Frequency MHz	Capacitance pF
1.0	1001.70 ± (0.44 + 0.01)

For the Director,
National Institute of Standards and Technology

Approved by:

Robert M. Judish, Sr. Project Leader
Microwave Metrology Group
Electromagnetic Fields Division

George M. Free
(303) 497-3609

Test No.
Date of Test:

BL-114A
(5-90)
ADMAN 15.01

U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

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A Calibration Service for Low Loss, Three-Terminal Capacitance Standards at 100 kHz and 1 MHz

5. AUTHOR(S)

George M. Free, Ray N. Jones

6. PERFORMING ORGANIZATION (IF JOINT OR OTHER THAN NIST, SEE INSTRUCTIONS)

U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
BOULDER, COLORADO 80303-3328

7. CONTRACT/GRANT NUMBER

8. TYPE OF REPORT AND PERIOD COVERED

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (STREET, CITY, STATE, ZIP)

10. SUPPLEMENTARY NOTES

This Technical Note is meant to satisfy the documentation requirement for three-terminal capacitor calibration service.

11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

This document describes the three-terminal, capacitance calibration service at 100 kHz and 1 MHz at the National Institute of Standards and Technology, Boulder Laboratories. The document discusses the purpose of the service, contact points for initiating the service, what capacitors are appropriate for calibration, the measurement methods used, the instrumentation used for the measurements, and an analysis of the errors in the measurement. It also lists the calibration uncertainties for the stated frequencies and capacitances. Finally, the document discusses the quality assurance programs used at NIST to insure the integrity of the calibration.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

calibration; capacitance; lead inductance; measurement; three-terminal; uncertainty

13. AVAILABILITY

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